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The Results of Initial Analysis of OSTA-1/Ocean Color Experiment (OCE) Imagery

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May 30, 1982

National Aeronautics and
Space Administration

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OSTA-1/OCEAN COLOR EXPERIMENT (OCE) IMAGERY**

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ABSTRACT

Ocean view images from the Ocean Color Experiment (OCE) were produced at three widely separated locations on the earth. Digital computer enhancement and band ratioing techniques were applied to radiometrically corrected OCE spectral data to emphasize patterns of chlorophyll distribution and, in one shallow, clear water case, bottom topography. The chlorophyll pattern in the Yellow Sea between China and Korea was evident in a scene produced from Shuttle Orbit 24. The effects of the discharge from the Yangtze and other rivers were also observed.

Two scenes from orbits 30 and 32 revealed the movement of patches of plankton in the Gulf of Cadiz. Geometrical corrections to these images permitted the existing ocean current velocities in the vicinity to be deduced. The variability in water depth over the Grand Bahama Bank was estimated by using the blue-green OCE channel. The very clear water conditions in the area caused bottom reflected sunlight to produce a sensor signal which was related inversely to the depth of the water.

THE RESULTS OF INITIAL ANALYSIS OF OSTA-1/OCEAN COLOR EXPERIMENT (OCE) IMAGERY

EXPERIMENTAL PLANS

The Ocean Color Experiment (OCE) was designed to map ocean features using an eight-channel scanning radiometer installed on the second orbital flight test of the National Aeronautics and Space Administration's (NASA) shuttle, Columbia. The operational principle of this instrument relied on a process whose feasibility has been recognized for some time.⁽¹⁾ For instance, NASA began in 1972 high altitude aircraft sensor investigations known as the U-2 Ocean Color Scanner (OCS) program.⁽²⁾ Then in October, 1978, the Coastal Zone Color Scanner (CZCS) was launched aboard the Nimbus-7 free flyer spacecraft to make periodic observations of ocean color primarily in coastal areas.⁽³⁾ The development of the concept of a shuttle-borne scanner was conceived in this environment and was based on the experience gained from these earlier instruments.

The primary goal established for the experiment was to demonstrate the ability to detect phytoplanktonic algae on a global basis and determine the chlorophyll pigment concentrations. In order to implement the scientific objectives, a team of scientific investigators (H. H. Kim, N. E. Huang, R. S. Fraser, C. R. McClain, L. R. Blaine from Goddard Space Flight Center (GSFC) and H. v.d. Piepin from DFVLR, W. Germany) was formed to formulate the experimental plan. The primary features of the plan are as follows:

(a) The OCE data collection was to focus mainly on deepwater areas in contrast to the purported objectives of the CZCS. This was to avoid the complicated spectral characteristics of coastal waters which are induced by the influence of the coastal marine constituents introduced by continental sources. The relationships between the radiometric spectra and water content are not well understood.

(b) The OCE was to address particular problems of the radiometry of the ocean-atmospheric system. The investigators realized that the albedo of the ocean is small compared to that of most land surfaces. For instance, less than 10 percent of the blue spectral radiance is returned to the atmosphere by oceanic scattering. Thus, most of the light received by the sensor in space would never have interacted with the subsurface water mass but would only have interacted with the molecular and particulate components of the atmosphere and the ocean surface. Therefore the experiment was to study the problem associated with the aerosols, sea state and other parameters which mask the perceived sub-surface oceanic radiance.

The scanner used for the shuttle experiment was originally built as an aircraft instrument by NASA-GSFC. It was modified to meet the shuttle payload specifications. By late 1979, the hardware development of the sensor was completed and it was mounted on the shuttle payload pallet by the spring of 1980. The allocation and characteristics of the eight spectral channels are summarized in Table 1. The signal-to-noise ratio was superior to that of the original aircraft instrument. The geometrical and optical design of the OCE gave it a swath of 506 km and an instantaneous field-of-view (IFOV) at nadir of about 1 km^2 at orbiter altitude. With this IFOV and a scan frequency of 4 rps, the scanner undersampled by a factor of 50 percent. This permitted a data recording rate which met the quota allotted to the OCE for storage on a recorder in the orbiter's cabin.

The general data plan of the OCE was to collect 120 minutes of data during the orbiter's passes over selected test sites. The sites chosen were known from previous experiments and experience to be likely to produce interesting chlorophyll distribution patterns which were produced, in some cases, by mesoscale anomalous flow patterns in the regions.

In order to augment the interpretation of the OCE results, the data plan included establishment of several in-situ data collection projects. These involved collecting ocean samples, ground

Table 1

Spectral Channel (nm)	Spectral Bandwidth (FWHM) (nm)	S/N Ratio	Peak Spectral Radiance (mW/cm ² -μ-sr)	Spectral Region	Purpose
1. 485.9	23	1200:1	53.7	Blue	Chlorophyll Absorption (max.) Atm. Rayleigh Scattering
2. 518.4	23	1400:1	37.8		Chlorophyll Hinge Point
3. 552.6	23	1200:1	26.8	Green	Chlorophyll Absorption (min.)
4. 584.5	23	1000:1	21.0		Backscattering (water and atm.)
5. 620.6	23	800:1	16.3		Backscattering (water and atm.)
6. 655.1	23	800:1	13.4	Red	Non-fluorescence band
7. 685.1	23	680:1	11.6		Chlorophyll Fluorescence at 685m
8. 786.6	52.4	550:1	7.5	Near Infrared	Atm. backscattering (Mie)

based observations of the atmospheric transmissivity, and correlative aircraft underflights. The location of predesignated test sites and participating experimenters were:

1. Off the Coast of Portugal

A. G. Fiuza, University of Lisbon, Portugal

H. van der Piepen, DFVLR, W. Germany

M. Viollier, University of Lille, France

2. Warm Core Eddy Rings in the Northwestern Atlantic

P. Wiebe, Woods Hole Institute of Oceanography

3. South Atlantic Bight

J. A. Yoder and L. P. Atkinson, Skidaway Inst. of Oceanography

4. Off the Coast of Costa Rica

V. Klemas, University of Delaware

5. Frontal Zones of the Kuroshio Current near Honshu Island

M. Takahashi, University of Tsukuba, Japan

In comparison to the originally planned 120 minutes, the OCE acquired 118 minutes of data during the orbiter's three-day flight which began on November 12, 1981 and terminated on November 14, 1981, after 54.25 hours. The ground tracks where the OCE data collection took place are shown in Figure 1. Many areas of the data acquisition were not the areas which had been designated in the original plan. The deviations from the original flight plans were caused by the following operational difficulties:

(a) The actual launch of the orbiter on November 12 was delayed by 3 hours from the originally planned 7:00 a.m. EST. This delay caused significant changes in the solar zenith angles at the target sites when the orbiter passed. Alternative orbital passes, mostly in ascending orbital portions, had to be selected to get proper solar zenith angles.

(b) Relatively low Sun angles in the month of November in the Northern Hemisphere substantially limited the number of chlorophyll target areas that could be selected.

(c) Also, because of spacecraft malfunctions, the STS-2 mission time was shortened by 2 days.

(d) During the mission, two large storm systems covered both the East and West coast of the U.S. The South Atlantic Bight which extends from Cape Canaveral to Cape Hattaras, S. Carolina was one of the OCE's important predesignated test sites. Thus relatively low percentage of cloud free scenes among the total data resulted in about 20 to 30 minutes of data out of the total 2 hours of data.

In spite of all these difficulties, the device acquired enough data to meet its basic objectives by demonstrating the ability to map chlorophyll concentration and identify ocean circulation features.

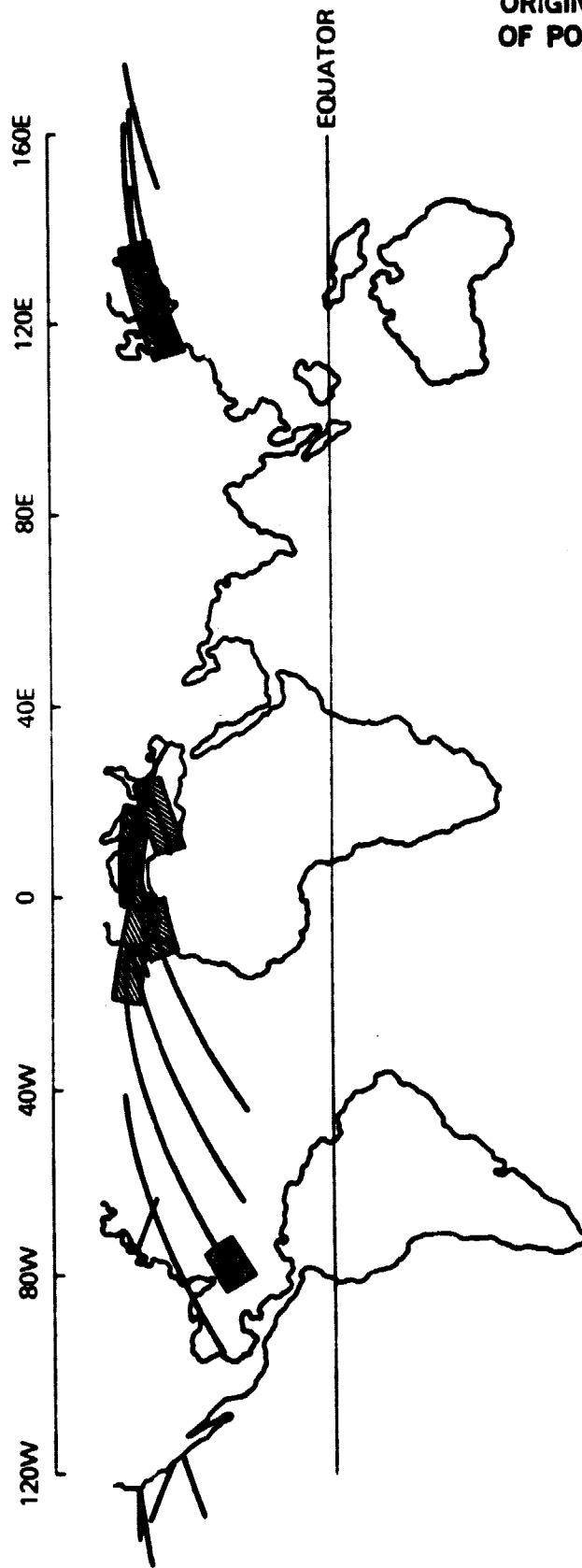


Figure 1. The Shuttle, "Columbia's", ground tracks where OCE data were acquired during November 12-14, 1981. The areal coverage of clear ocean view data that were of sufficient quality to process are shown in hatched areas.

Excellent ocean scenes from some of unplanned areas became available from the mission. Segments of the OCE data which show clear ocean views are:

<u>Orbit No.</u>	<u>Time Segment D/Hr/Min/Sec (GMT)</u>	<u>Geographical Location</u>
24	318:01:32:00 318:01:42:15	Yellow Sea/Sea of Japan and Pacific Ocean
29	318:09:00:00 318:09:04:00	Gulf of Libya/Greece (partially cloud covered)
30	318:10:28:00 318:10:36:15	Portugal Coast and Med. Sea
31	318:12:08:00 318:12:15:00	Spanish Coast to Italy (partially cloud covered)
32	318:13:20:30 318:13:26:00	Great Bahama Bank
32	318:13:39:00 318:13:42:15	Strait of Gibraltar

In addition to the above OCE data, coordinated low flying aircraft data taken with a similar instrument flown by a West German team, and shipborne measurements of oceanic parameters from the Portugese coast are available for November 10-14, 1981.

It will require some time to process, analyze, and correlate the OCE observations with the ground truth and aircraft data. However, initial assessments of the OCE data are given in the following sections.

CHLOROPHYLL ANALYSIS

Figure 2 is a false color image of the Yellow Sea showing the chlorophyll distribution of the area on November 13, 1981. The data were taken as the orbiter emerged from mainland China and headed toward the Japanese Islands during its 24th orbit. The image is created by ratioing the difference of data from Bands 1 and 3 to their sum after the atmospheric obscuration effects are calculated and subtracted by using Band 8 (near IR) data. The chlorophyll features are

Figure 2. A map of chlorophyll pigments in the Yellow Sea on November 13, 1981, from STS-2 Orbit 24. This false color image shows the distribution patterns of chlorophyll pigment bearing phytoplankton. The color bar scale gives the quantity of pigments associated with each color in the figure.

digitally enhanced. The scaling of the pigment concentration was done by using the following empirical relationship which defines a correlation between the shipboard measurement of concentration, C, and the derived water radiance products, R:

$$C = 17.5 \text{ Exp } (-5.44 \times R)$$

Where

$$R = \frac{I^W(482\text{nm}) - I^W(552\text{nm})}{I^W(482\text{nm}) + I^W(552\text{nm})}$$

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The $I^W(\lambda)$ is the ocean spectral radiance obtained after applying a correction to eliminate the atmospheric radiance. Table 2 lists all the radiance components of an OCE data set from Figure 2. This particular set was taken from an area just east of the Cheju Island. Quantitative estimates of surface chlorophyll requires that the contributions of backscattered radiation from the atmosphere (last column) and the sea surface (column 7 of Table 2) removed from the total upwelling radiance measured in the Column 1.

In OCE radiative analysis, a proven atmospheric radiative transfer computation method commonly known as Dave Code was used.⁽⁴⁾ In the analysis, an effective albedo of the lower boundary is determined for each pixel using total upwelling radiance measured by the scanner (2nd column). Certain reasonable assumptions are needed to construct an appropriate atmospheric model. The primary assumption is that the particle sizes of the aerosols are distributed according to the Jungean size distribution with a Jungean parameter 3.0. This model gave upwelling radiance values of 0.22 for Rayleigh sky conditions and $0.56 \text{ mw/cm}^2 \cdot \mu\text{-sr}$ for a columnar aerosol content of 2.77×10^8 . The measured OCE radiance of the 786nm was 0.37 as shown in Table 2 from which a particle content of 1.55×10^8 was interpolated from the model and used as input to the calculations for other channels.

For image processing, such computation processes can be performed for each picture element, on a pixel by pixel basis, to construct an entire ocean image corrected for atmospheric effects.

Table 2
Radiance Components: OCE Orbit 24
Loc: 33°:15N, 126°:40E Time: 318:01:34:00 (GMT)
SZA = 56°, Azimuthal Angle = 70°

OCE Band	Measured Rad.*	Effective Albedo (%)	Downwelling Fluxes†			Upwelling Rad.*			
			Total	Sun.	Diffused	Fresnel	Total	Water	Atm. Rad.
1	3.92	3.4	96.3	70.3	26.0	0.08	1.04	0.96	2.88
2	2.75	2.15	92.4	70.6	21.7	0.069	0.63	0.561	2.12
3	2.00	1.7	89.0	71.2	17.7	0.057	0.48	0.423	1.52
4	1.49	0.95	90.2	72.9	17.2	0.049	0.27	0.221	1.22
5	1.00	0	81.5	67.8	13.7	0.041	0.041	0	0.96
6	0.88	0	82.6	69.9	12.7	0.036	0.036	0	0.88
7	0.69	0.35	78.4	67.3	11.1	0.031	0.07	0.04	0.62
8	0.37	0	65.2	57.5	7.7	0.004	0.004	0	0.366

*(mW/cm²-μm-sr)

†(mW/cm²-μm)

However, such measures would require a considerable amount of computer processing time. Alternatively, the method of taking a proportionality constant between the atmospheric channel and other visible channels has been discussed elsewhere.⁽²⁾

These atmospheric effects correction algorithms were repeatedly tested using high altitude U-2 aircraft data which were taken during the oceanographic field experiments studying Gulf Stream frontal eddies in 1979 to 1981. These aircraft experiments have given us valuable experience to refine our atmospheric effects correction algorithms. Also they have provided us with an empirical relationship which correlates the shipboard measurements of chlorophyll concentration with the derived radiance ratios.

It is important to note that the quantitative assessment of chlorophyll is valid only in cases of open ocean waters. The total upwelling spectral radiances of the open ocean water vs. coastal

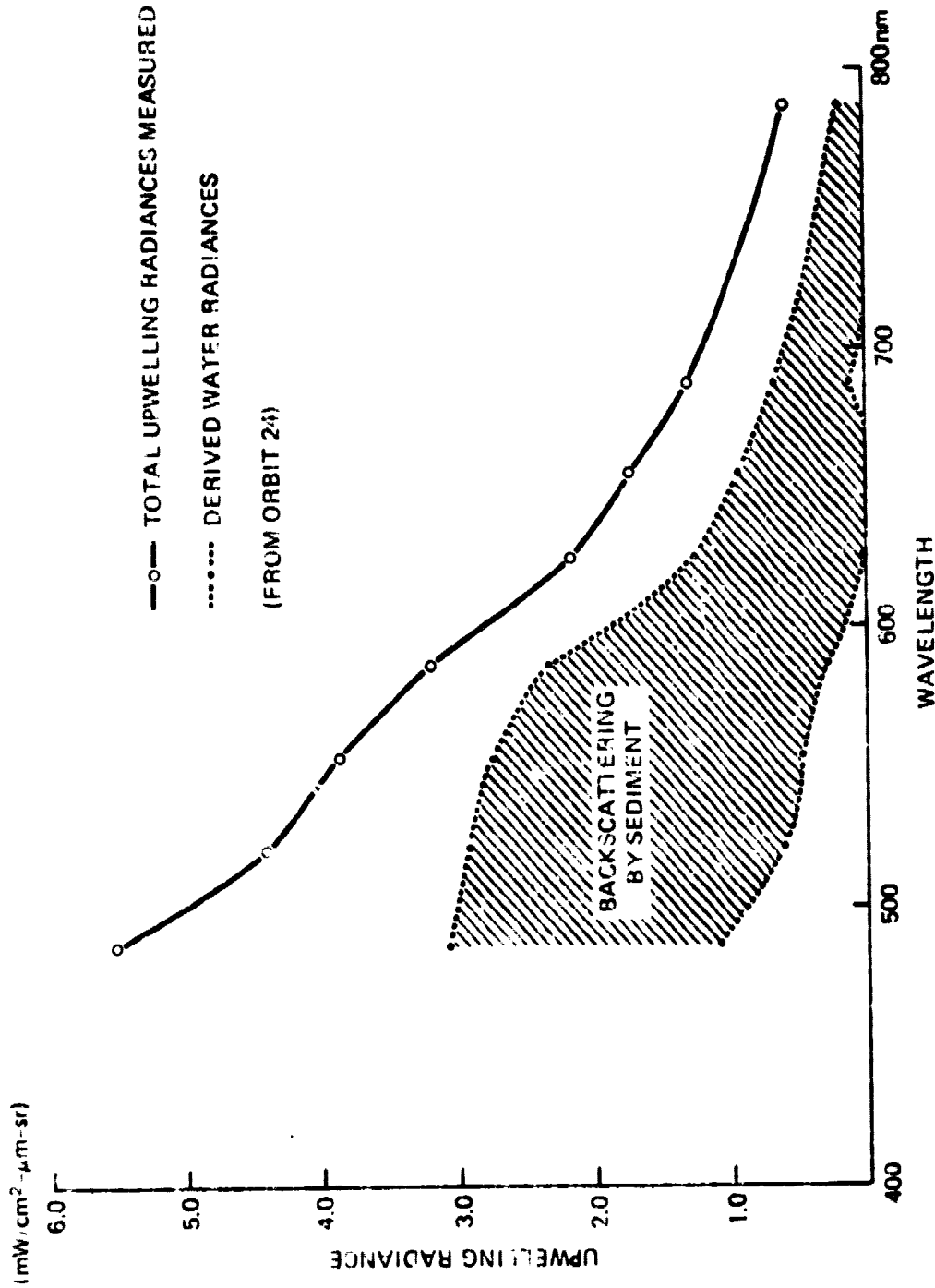


Figure 3. Upwelling spectral curves from two selected areas of the Yangtze scene in Figure 2. The top solid curve is the total upwelling radiance of the river plume perceived by the scanner. Upper dotted line corresponds to the derived water radiance of the plume. For comparison derived water radiance for the open ocean water case from just east of the Cheju Island is shown in lower dotted line. The hatched area corresponds to the portion of radiance attributed to the backscattering of sediments.

nature can be seen in the same scene. Figure 3 pertains to such upwelling spectral radiances of a clear water case, obtained from a point just East of the Cheju Island, and of a turbid water case which was sampled from a pixel in the middle of Yangtze River plume shown in black shade in Figure 2. The upwelling spectra of the river plume show considerable enhancement in the regions of Bands 3 to 8 indicating that the area plume contains significant amount of sediment particles as well as perhaps high chlorophyll concentration. Knowledge of radiative transfer in the turbid water still remains too incomplete to provide reliable chlorophyll data products of this zone. In any event, the absence of strong shelf circulation in the area causes remarkable plume patterns in the discharge from the Yangtze easily distinguishable from the surrounding waters.

REMOTE MEASUREMENT OF CURRENT VELOCITY

R. Legeckis in 1979⁽⁵⁾ reported how high resolution thermal infrared data from polar orbiting satellite can be used to track water features in currents. One example is the time variation in the flow of the Gulf Stream between Florida and Cape Hatteras. Similarly, visible color imagery of the ocean offers another interesting means of assessing current patterns. The spatial resolution of the visible imagery in general is better than the thermal imagery and the measurement of the current velocity based on the chlorophyll patch drift patterns is more precise and directly related to the water mass transport phenomena. An opportunity to demonstrate the possibility of using color images to measure ocean circulation occurred when the Shuttle passed over the entrance of Gibraltar Strait twice on the same day. As shown in Figures 4 and 5, similar chlorophyll contour images of the Gulf of Cadiz were taken from Orbit 30 and 32 as the orbiter passed over the area at 10:32 a.m. and 1:40 p.m. on November 14, 1981. In these images areas of high chlorophyll concentration are represented by darker shade. What appears to be an elongated chlorophyll feature which stretches from the entrance of the Gibraltar Strait to the middle of the Gulf of Cadiz and then curls north toward the southern Spanish shore is visible in both images. However, careful geometrical corrections allowed observation of changes in the shape and relative positions of the patches during the 3 hour time span. Figure 6 is a schematic diagram



Figure 4. Chlorophyll image of the Gulf of the Cadiz taken on November 14, 1981 (GMT) from STS-2, Orbit 30. The elongated dark feature, in center, stretches from the entrance of the Gibraltar Strait to the southern Spanish shore.

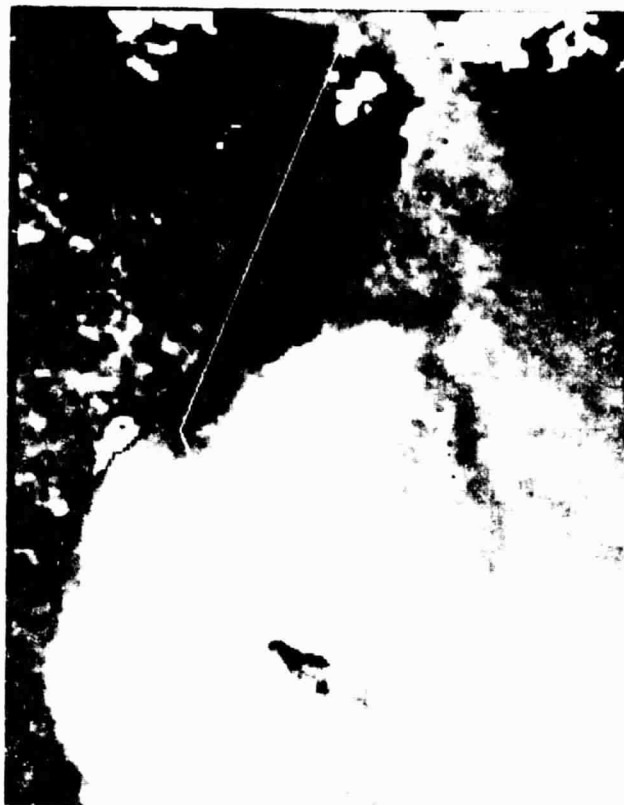


Figure 5. The same chlorophyll features in Figure 4 are also visible in this OCE image which was taken 3 hours later from Orbit 32. Careful measurements of the salient features reveal motion of the chlorophyll patches.

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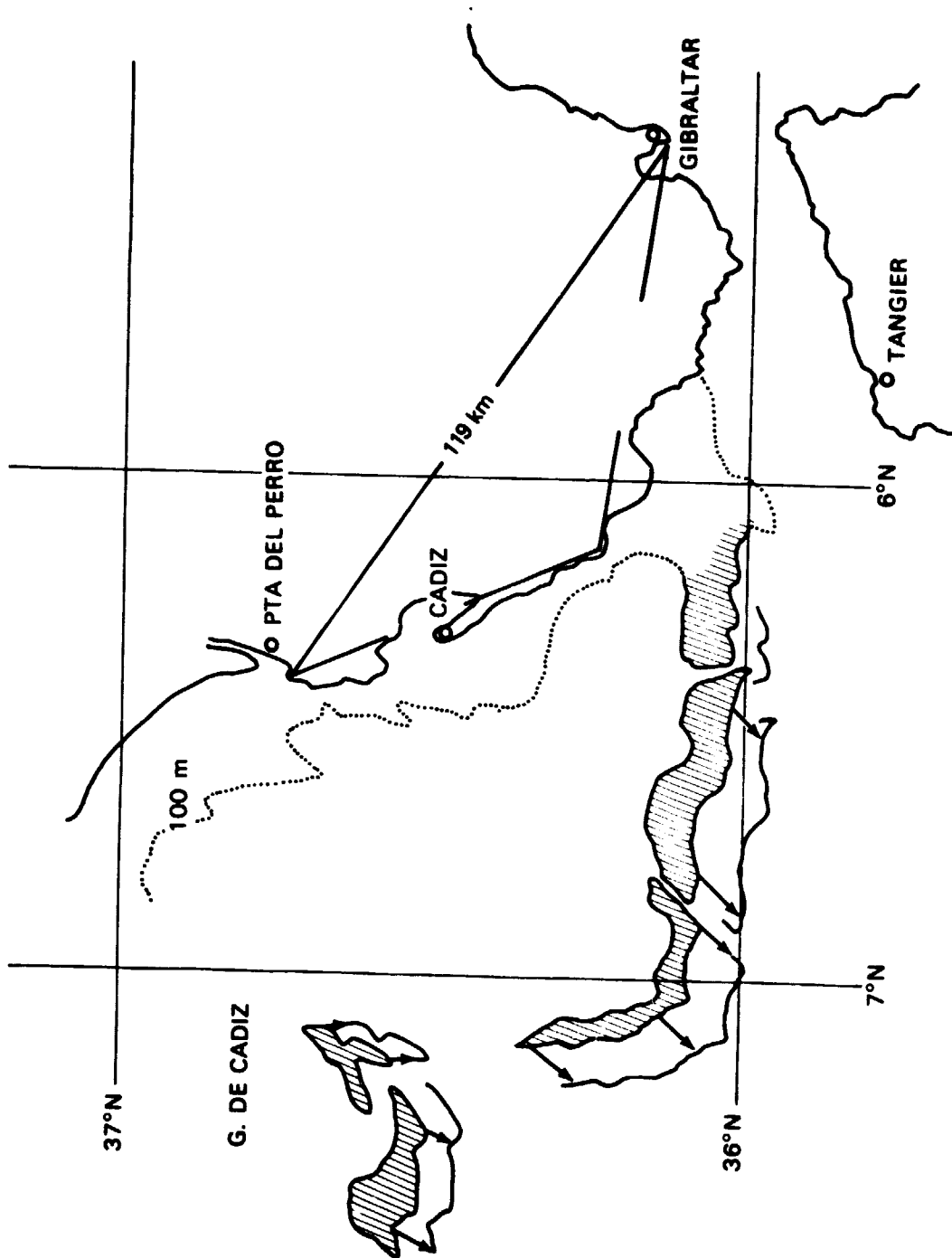


Figure 6. Relative motion of chlorophyll patches is given in exaggerated vectors. The presence of a clockwise circulation in the Gulf of Cadiz on November 13, 1981, is suggested by the directional patterns of the patch drift.

which illustrates the net motion of the chlorophyll patches. The positioning of the feature was accomplished by triangulating several salient features of the patches relative to three on-shore anchor points located near the water edge. The spatial resolution of the ratio corrected OCE imagery provides accuracy of 0.5km. Analysis of the images showed relatively rapid southeastward movement, away from the Gibraltar entrance at a rate of 5.5km (11 pixels) in 3:10 hours and relatively slow southwestward flow at a rate of 2.0km (4 pixels) in 3:10 hours along the shallow coastal lines. The net motion depicts the presence of an anticyclonic circulation in the Gulf. Ultimately the compatibility of the OCE data analysis with the sea-truth will have to be tested when the buoy measurements and wind field data for November 14, 1981 become available. However, near the Strait entrance historical current measurements show a strong surface current in the upper 100 meter layer which flows into the Mediterranean sea along the coast of N. Africa and Spain. Also, a relatively saline Mediterranean undercurrent flows out from the narrow strait at greater than 100 meter depth and surfaces at some distance into the Atlantic.

BATHYMETRY

The Great Bahama Bank forms a semicircular shoal whose depth ranges from few meters to tens of meters. Gradients in depth occur at the northern edges known as the Tongue of the Ocean. This interesting topographic feature is surrounded with sea water with low oxygenation. Thus the area is characterized by the scarcity of the planktonic forms of marine life. Combination of the above circumstances make the area among the clearest ocean water area suitable for visual observation of the underwater topography. The blue-green components of visible light in the absence of chlorophyll pigment, penetrate deep into the water and reflect from the bottom and yield return signals. The data taken from Orbit 32 at 8:24 a.m., (EST), in the vicinity of Nassau and Andros Islands were processed to depict the under water topographic features of the Bank as shown in Figure 7. The enhanced false color image is based on the upwelling radiance of the 518nm band. The return signal is related inversely to the depth of the water. The upwelling spectral radiances taken from a shallow zone and from a deep water zone of Figure 7 are

Figure 7. False color image of the Great Bahama Bank and its vicinity on November 14, 1981, 8:25 a.m. (EST) from Orbit 32. The ocean depth is depicted by the various colors assigned by the color bar.

shown in Figure 8. The dotted lines of water sub-surface radiance are corrected for the atmospheric effects. The hatched areas represent signals which are from the bottom reflections.

The differences between the spectra of bottom reflection in Figure 8 and that of the sediment laden backscattering in Figure 3 are interesting. These spectra clearly illustrate the difficulties one can encounter in analyzing coastal chlorophyll.

DISCUSSION

Because of the orbiter's shortened mission, the OCE netted only a minimum amount of clear ocean view data. Also some of the surface experiments designed to validate interpretations of OCE observation were not carried out because of the delays and rescheduling of the Shuttle launch date.

In spite of these difficulties, the authors believe, the primary objectives of the OCE were achieved. The three cases presented exemplify a wide variety of ocean phenomena that were observed and analyzed from the color expressions of the ocean.

The OCE has demonstrated that, properly treated, the ocean colorimetry will provide a simple and direct method of remote sensing of the oceans. Up to now, oceanographic studies incorporating satellite imagery of visible color would be limited to inferring near shore and estuarine circulation. In those regimes, a high reflectivity by suspended material provides relatively easy signature to identify. The method of detecting variation in chlorophyll concentration in spatial and time domains promises a new dimension.

In order to measure the concentrations of phytoplankton pigments in the ocean, the radiance detected at satellite altitudes needs to be corrected for the atmospheric effects. The method devised to remove the aerosol effects for CZCS is a possible alternate method.⁽⁶⁾ But in our OCE analysis, a sophisticated model was incorporated to account for all the components in absolute radiance as given in Table 2. The outcome of such a method provides us with a consistent

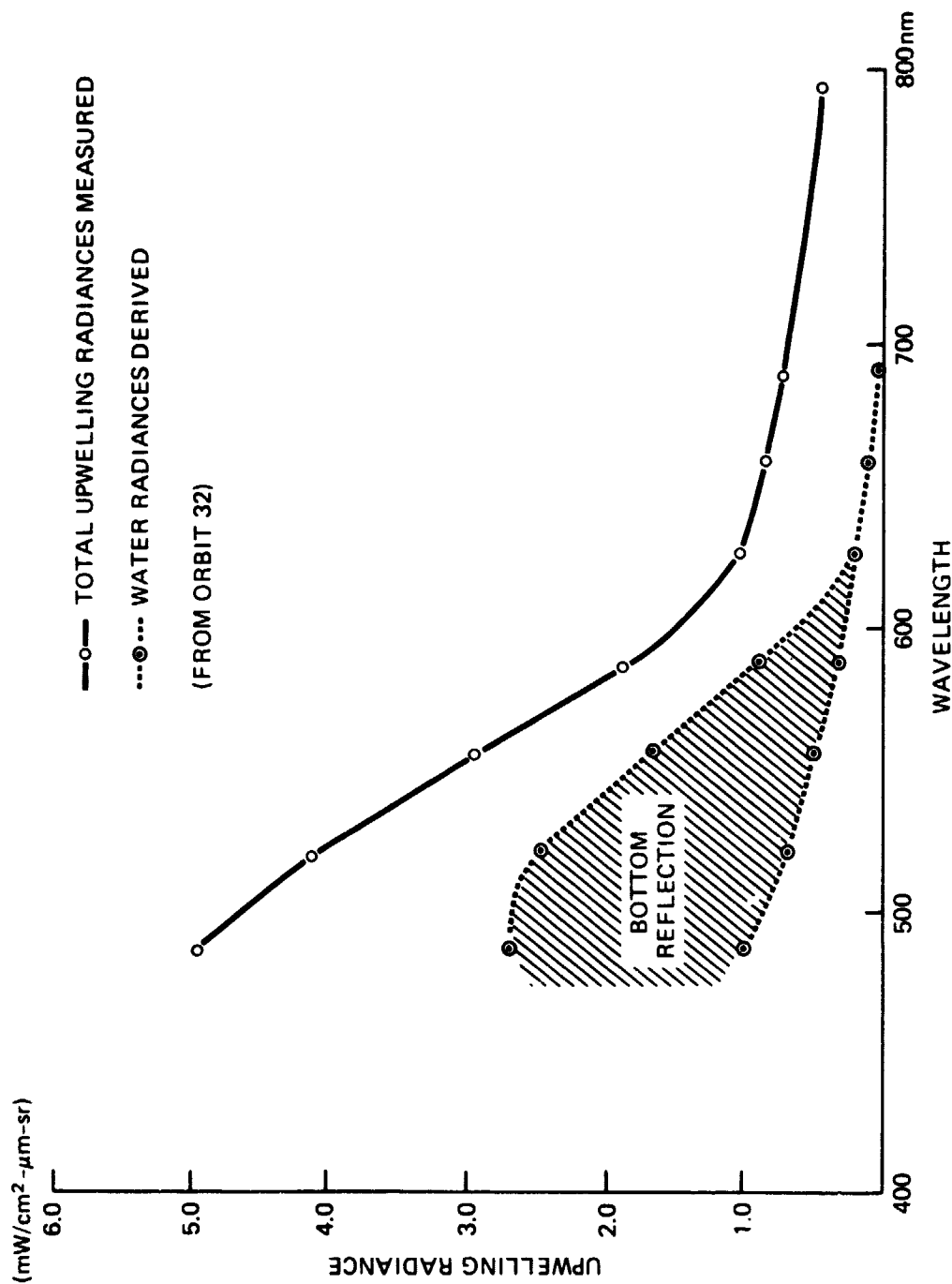


Figure 8. Upwelling spectral curves from two selected areas of the Great Bahama Bank scene (Figure 7). The top solid curve is the total upwelling radiance from a shallow zone perceived by the sensor, and upper dotted line is the derived water radiance. The derived water radiance from a deep water, the Tongue of the Ocean area, is given in dotted line lower case. The hatched area corresponds to the portion of radiance attributed to the ocean bottom reflection.

relationship between the signal measured and the concentration of the chlorophyll pigments in the open ocean.⁽⁷⁾ However, the spectral curves in Figures 3 and 8 imply that chlorophyll analyses are still limited to the type of oceanic conditions of hydrospheric homogeneity and clarity.

The method of using chlorophyll concentration as tracers promises an interesting aspect in deducing oceanic flow patterns of a large area (Figure 6). Plankton patches are a natural drifter which can be tracked by satellites. Thus the color scanner, properly operated, has proven to be directly applicable to studies of circulation models and features in addition to studies of biological processes. Finally, the analyses and results in this paper are only an initial assessment and other in depth studies by colleagues are expected to follow. Those data of clear ocean view listed in page 6 will be archived at the National Space Science Data Center (NSSDC) located at the NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771, and will be made available to the public.

ACKNOWLEDGMENT

An experiment as complex as this OCE involves many individual and space is too limited to acknowledge the contributions of each individual. However, the authors would like to make a special acknowledgment of the contribution rendered by two project engineers at GSFC, Dave Clem and Bertrand Johnson, who were responsible for the flawless performance of the OCE instrument during the mission.

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